



## Performance of Mortar Incorporating Heat-Treated Drinking Water Treatment Sludge as a Silica-Sand Replacement

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### Abstract

This paper examines the possibility of using water purification wastes in the production of mortar. Within the study context, XRD and XRF analyses were performed to obtain the chemical composition of sludge. Moreover, heat-treated sludge at a temperature of 900°C was used in the preparation of mortar mixes as a partial sand replacement (5, 10, 15, and 20% by sand weight) with a w/c of 0.48. Fresh mortars were tested for workability, and mortar samples with 7, 28, and 90 days curing ages were tested for dry density, absorption, ultrasonic pulse velocity (UPV), and compressive and flexural strengths. Besides, some regression modeling was conducted for each of the measured parameters. In general, the results showed that the use of up to 10% incinerated sludge by sand weight leads to a slight decrease in the workability and density of the mixture and a 10% increase in its strength. Nevertheless, mortars with sludge content of over 10% showed a significant increase in water absorption and a decrease in strength and other properties.

**Keywords:** Water Purification; Incinerated Sludge; XRD and XRF; Sludge Management; Sand Mining; Absorption Test.

## 1. Introduction

The construction industry greatly contributes to consuming natural resources as raw materials. Over the last few decades, the mining activities of raw materials have significantly increased as the construction sector grows. For example, the consumption of sand and gravel is estimated to be around 32–50 billion metric tons each year [1]. In 2011, the United States (US) produced 810 million metric tons of sand and gravel. About 40% of them were used in the construction sector as concrete aggregates, asphalt concrete aggregates, construction fill, etc. [2]. Currently, several potential concerns about the biological and hydrological environment are associated with the production and use of sand. Pitchaiah [3] showed that sand mining significantly impacts vegetation, soil profile, water tables, water quality, noise and air pollution, river geometry, etc.

On the other hand, the demand for potable water is being escalated by population growth. The estimation showed that the world population will increase to reach nearly 9.2 billion in 2040 [4]. As a result, the demand for surface and groundwater sources will rise. Indeed, most surface water sources are not pure enough. Thus, they require treatment before distribution. At the treatment plant, water goes through many processes such as coagulation, flocculation, sedimentation, filtration, and disinfection. These processes produce a significant amount of precipitate called sludge.

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The quantity of produced sludge will vary depending upon the water's characteristics, the treatment mechanisms, the quality of water estimated to be produced, and the quantity of water to be treated each day [5]. Regardless of these factors, the daily production of sludge is estimated to be 10,000 tons for conventional Water Treatment Plants (WTP) on a global scale [6]. The sludge composition mainly consists of inorganic matter (i.e., silt, clay, and coagulant products). Options for the disposal of these wastes are summarized as follows: part of sludge discharges into wadis, drains, streams and rivers, especially in developing countries, which adversely affect the environment. Another part is used as a soil conditioner in agricultural fields, while most sludge's final destination is usually landfilled. The first and third options contribute to economic and environmental burdens. Thus, alternative disposal options have to be considered for the water treatment sludge. Using such wastes as building materials contributes to protecting the environment and reducing the consumption of natural resources. González et al. [7] conducted an experimental study on cement replacement by drinking water sludge to check the compressive strength of mortar samples. The sludge was incinerated at 600°C and 800°C for three hours and then used as a 10% and 30% partial replacement of cement. Results showed potential for the use of 10% sludge replacement incinerated at a temperature of 600°C in the composition of mortar based on XRD and XRF tests, the compositions of sludge ash were classified as pozzolan material class F according to ASTM's standards.

Alzoubi et al. [8] examined the hardened properties of concrete by using water purification sludge in concrete mixes. The sludge was firstly incinerated at 800°C for two hours, ground, well-graded, and used in percentages of 5%, 10, 15%, and 20% by weight of fine aggregates. The study concluded that using sludge enhanced concrete's mechanical properties and significantly affected its workability. Furthermore, the study conducted that the compositions of incinerated sludge have the potential to be pozzolanic materials. Rodrigues and Holanda [9] investigated the effect of drinking water sludge on mechanical and physical properties such as apparent density, water absorption, and compressive strength of soil-cement bricks. Mixtures of soil-cement containing sludge up to 5 wt.% of sludge as a partial replacement of soil were prepared and treated for 28 days of curing. The study conducted that the used water treatment plant sludge increases the absorptivity of produced bricks and decreases the density and compressive strength. The study also mentioned that the sludge could be used for the production of such types of bricks.

de Godoy et al. [10] performed an experimental study using water treatment sludge as a Supplementary Cementitious Material (SCM) in mortars. The sludge was firstly burned for one hour at the temperature range of 600°C– 800°C and used in mortar mix with percentages of 14%, 35%, and 50% by weight of cement. The chemical and mineralogical analysis results showed significant evidence of pozzolanic activity of sludge due to the calcination process. Furthermore, compressive strength results showed great potential for the production of blended and pozzolanic Portland cement.

Many experimental research efforts have been conducted to investigate the applications of drinking water sludge in the development of construction materials, such as the utilization of sludge in ceramics making [11], in the manufacture of cement [12], and to replace sand in making concrete paving blocks [13]. However, sludge application as a sand replacement building material has not been explored enough.

The porous texture is one of the main properties of fine aggregates, resulting in a considerable amount of water being absorbed. As water purification sludge shows similar characteristics, it may be used directly as sand substitution in producing mortars and concrete in its raw form, without treatment.

The context of this paper focuses on the use of incinerated drinking water sludge as a partial replacement for sand in the preparation of mortar mixes. The physical and chemical characteristics of collected samples of sludge have been investigated by performing XRD, XRF, and some other tests. Mortar samples have been subjected to fresh and hardened tests in order to obtain the absorption, setting time, flow of hydraulic cement mortars (flow ability), ultrasonic pulse velocity (UPV), compressive strength, and flexural strength.

## 2. Materials and Methods

Indeed, with industrial and urban expansion, the amount of drinking water treatment sludge has increased significantly over the past years. As a result, it is important to find a suitable recycling technique to limit the volume of solid waste in the world. Recently, the utilization of industrial wastes in the production of concrete has played a significant role in the development of sustainable construction materials [14]. Accordingly, this study aims to investigate the performance of mortar incorporating heat-treated drinking water treatment sludge as a silica-sand replacement. Within the study context, properties of the sludge will be obtained experimentally, and the performance of mortar mixtures with various percentages of incinerated sludge will be highlighted. The methodology used in this study to achieve the research objectives is shown in Figure 1. In general, the research objectives will be set first, then a literature review regarding this topic will be discussed. Once the first stage is done, the properties of the sludge and other construction materials will be highlighted, and the experimental program to be followed in line with this research will be defined. Thereafter, the results obtained experimentally will be preprocessed, and regression models will be developed. Finally, a discussion of the study's results will be provided.

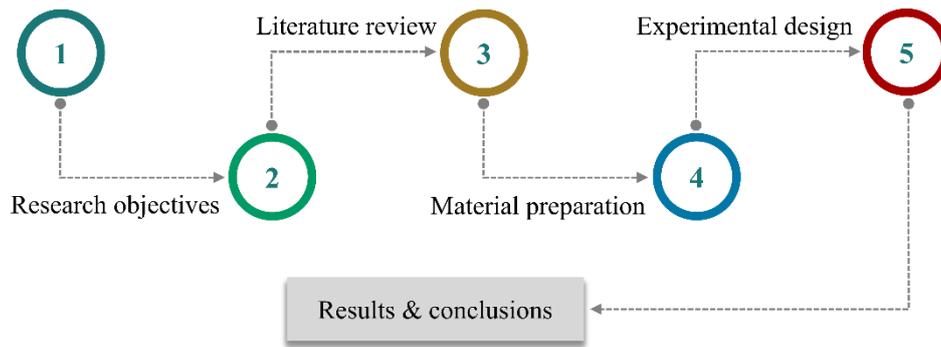


Figure 1. Methodological framework used in the study

2.1. Material Properties

The sludge samples were taken from the Zai Water Treatment Plant in the region of Al-Balqa, Jordan. This plant treats about 250,000 cubic meters per day of blended surface and groundwater conventionally. The treatment process starts with coagulation and flocculation, followed by sedimentation, filtration, and disinfection. Ferric salts are used as coagulant agents, while powdered activated carbon (PAC) is continuously injected to remove organic matter, taste, and odors. Sludge is pumped out to the drying beds to reduce the moisture content and then transported to landfills. Sludge samples were collected once a week from June to September from the drying beds. After collection, samples were tested for some physical and chemical properties, as summarized in Table 1. Additionally, X-ray diffraction (XRD) patterns of sludge were obtained with an X-Ray Diffractometer (Shimadzu, XRD-7000), monochromatic radiation of Cu-K $\alpha$  radiation with ( $\lambda = 1.54059 \text{ \AA}$ ) wavelengths at a rate of  $1.5^\circ (2\theta)/\text{min}$ , where Cu-K $\alpha$  is an x-ray energy frequently used on labscale x-ray instruments,  $\lambda$  is the wavelength of the incident X-ray beam, and  $\text{\AA}$  is the common wavelength unit known as Angstrom. As shown on the (XRD) diagram (Figure 2), sludge is a material that is mainly made of calcite crystallized mineral and quartz

Table 1. Elevation of used structures

Parameter	Value
pH	6.8 - 7.3
Specific gravity (SG)	2.1
Moisture content	11% - 16%
Volatile matter	2.92% - 8.75%
Water absorption	12%
Specific surface area ( $\text{m}^2/\text{kg}$ )	1100

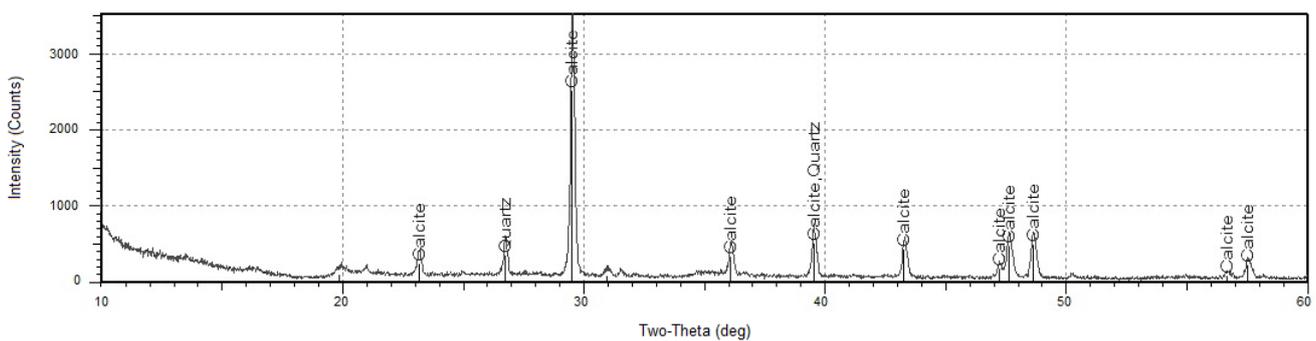


Figure 2. X-Ray Diffraction analysis of the incinerated sludge

In order to enhance the calcination process, sludge was milled after drying for 24 hours in an oven at 103-105°C and cooling. Thereafter, sludge is calcined in a muffle furnace at a temperature of 900°C for two hours with frequent rabbling. Figure 3 shows the sludge samples after being incinerated. Subsequently, the chemical compositions of untreated and incinerated samples were determined by an X-Ray fluorescence spectrometer (Shimadzu, XRF-7000), as shown in Table 2. The results of XRF show high content of iron oxide, silicon dioxide, and aluminum oxide. Both rocks and soils are the main sources of silicon, aluminum, and calcium, while ferric salts used in the coagulation processes are most likely to be the main source of iron [8]. However, the heat treatment process of sludge leads to an increase in the silica and alumina content, usually formed due to the thermal oxidation of silicon and aluminum. It is also demonstrated that a considerable amount of organic matter was removed in this process.



Figure 3. WTP sludge after incineration at 900°C

Table 2. The XRF results for the chemical composition of incinerated sludge

Constituent	Untreated sludge (%)	Calcined sludge
CaO	27.8	33.5
SiO <sub>2</sub>	21.3	25.3
Fe <sub>2</sub> O <sub>3</sub>	16.4	18.6
Al <sub>2</sub> O <sub>3</sub>	15.2	16.12
MgO	2	1.9
K <sub>2</sub> O	1	0.79
P <sub>2</sub> O <sub>5</sub>	1	0.81
Other	5	0.4
Loss on ignition	10.3	2.58

Thereafter, the incinerated sludge was sieved by using a mechanical shaker machine following the ASTM C136 test method. Figure 4 shows the particle size distribution of the used sludge and sand. Sludge particle size ranges between 600 - 300 μm and has a fineness modulus (FM = 1.2) with a specific area of 1100 m<sup>2</sup>/kg. Sludge particle size distribution has met the requirements of ASTM C778 [15].

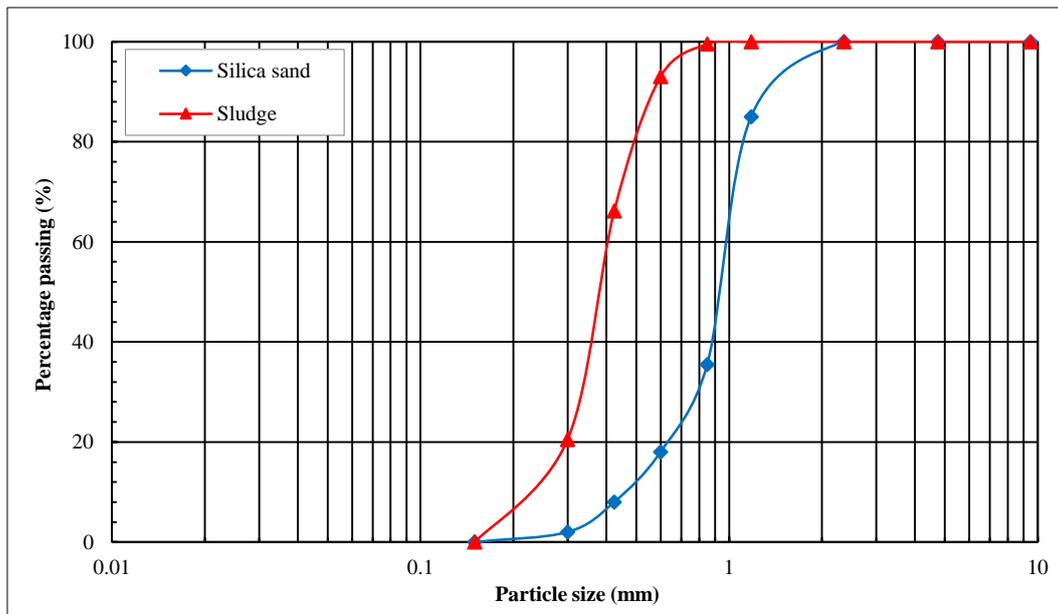


Figure 4. Particle size distribution of water treatment sludge and silica sand

Ordinary Portland cement (OPC) Type 1 confirmed to ASTM C150 with specific gravity = 3.15 was used in this study. Moreover, natural silica sand conforming to the requirements of ASTM C778 was used. The specific gravity, fineness modulus, absorption, and specific surface area of the sand were measured as 2.63, 2.7, 1.1%, and 880 m<sup>2</sup>/kg, respectively.

## 2.2. Mixture Proportioning and Design

For this study, many trial mortar mixes were prepared by replacing the sand with different % of incinerated sludge (5, 10, 15, and 20% by weight). For each mortar mix, six specimens were prepared to determine the mechanical strength at different curing ages. The water to cement ratio of 0.48 with a mix proportion of 2.75:1 by weight of sand + sludge to cement was kept constant for all batches following ASTM C109/C109M. Table 3 lists mixture proportions for all mortar samples, in which, for example, M1-C refers to the control mix, M2-5% refers to sludge to replace silica-sand at 5% replacement, and so on. The materials were mechanically mixed according to the procedure given in ASTM C305.

**Table 3. Mix proportion of mortar mixes**

Mix No.	Cement (g)	Silica sand (g)	Incinerated sludge (g)	Water (g)
M1-C	1250	3437.5	0	600
M2-5%	1250	3265.625	171.875	1050
M3-10%	1250	3093.75	343.75	1050
M4-15%	1250	2921.875	515.625	1050
M5-20%	1250	2750	687.5	1050

However, to investigate the effect of the addition of incinerated sludge on hardened mortar properties, mortar specimens were subjected to flow table, density, absorption, compressive strength and flexural strengths, and ultrasonic pulse velocity (UPV) tests.

## 2.3. Experimental Program

After the initial 24 hours of drying, all mortar samples were demolded. The specimens for the tests on the basic mechanical characteristics (compressive and flexural strength) were submerged in a water tank at a room temperature of 20°C. The flow of fresh mortar indicates the workability of the mixtures. The determination of the flow spread diameter was performed as per ASTM C1437. The standard conical mold (50 mm in height, top diameter = 70 mm, and base diameter = 100 mm) was placed at the center of the flow table and filled with fresh mortar samples in two layers. Each layer was tamped 20 times with the tamper rod. Excess mortar on the top surface was a stroke off with the straightedge utilizing sawing motion across the top of the mold, taking care to remove any water from the area around the base of the mold. Immediately, the mold was removed from the table within 15 seconds of full filling the cone, the table was then jarred 25 times within 15 seconds, and a caliper was used to measure the diameter of the spread mortar.

The dry density of hardened mortar was determined as per BS EN 1015-10 [16]. Three mortar test specimens of known volume were prepared and cured for 7, 28, and 90 days. The samples were then dried at a temperature of 70°C, weighted, and the dry density was calculated. Water absorption is an important property of cement-based materials, as it may affect their durability. Tests for the water absorption rate of mortars were accomplished in compliance with ASTM's standards. After 24 hours of mixing time, six cube specimens 50-mm aside were removed from the molds and cured in sealed plastic bags for 7,28, and 90 days. The samples were then dried in a ventilated oven at a temperature of 110°C for 24 hours until the weight change difference was less than 0.2 % over one hour. After 48 hours of cooling, the samples were ready and tested following ASTM C1403 [17].

A Hobart A200 20 QT Mixer was used for sample mixing. Before adding sand, cement and water were mixed for 30 seconds at low speed. Sand and sludge are then added to the mixture for two minutes of mixing, the first minute at low speed and at fast speed for the second. Figure 5 shows mortar samples after demolding.



**Figure 5. Mortar samples after demolding**

For the compressive strength test, mixtures were cast in 50 mm cubes samples for 24 hour period. After demolding, the cube specimens were subjected to compressive stress after 7, 28, and 90 days of water curing at room temperature. The obtained results represent the mean value of six tests performed following ASTM C109/C109M. The specimens were tested through a 0.33 MPa/s loading rate on the Compression Testing Machine until they failed.

The flexural bond strength tests were performed using ASTM C348 by preparing six samples of 40×40×160 mm test prisms. The prisms were molded by tamping in two layers, cast for 24 hour period, stripped out of the molds, and kept in water for 7, 28, and 90 days of curing age before testing by center-point loading. The beams were examined using the flexure testing machine shown in Figure 6 at a 0.5 kN/s loading rate.



Figure 6. Three-point bending test on mortar prisms

In order to assess the quality of mortar in terms of uniformity, density, imperfections, and other factors, the nondestructive ultrasonic pulse velocity (UPV) test was performed in accordance with ASTM 597. The test was accomplished by passing an ultrasonic pulse wave generated by an electro-acoustical transducer type ux4600L through the mortar samples. The higher quality of mortar obtains higher ultrasonic pulse velocity and vice versa.

### 3. Results and Discussions

#### 3.1. Workability of Fresh Mortar

The variations of the flow table resulting from the use of incinerated sludge in the production of mortars are shown in Figures 7 and 8. The results show a slight decrease in the fluidity of mortars with low sludge content (up to 10%), while the increase in sludge content leads to a noticeable reduction in workability. The same pattern was seen in the studies of Dunster et al. [18], Li et al. [19], and Vouk et al. [20].

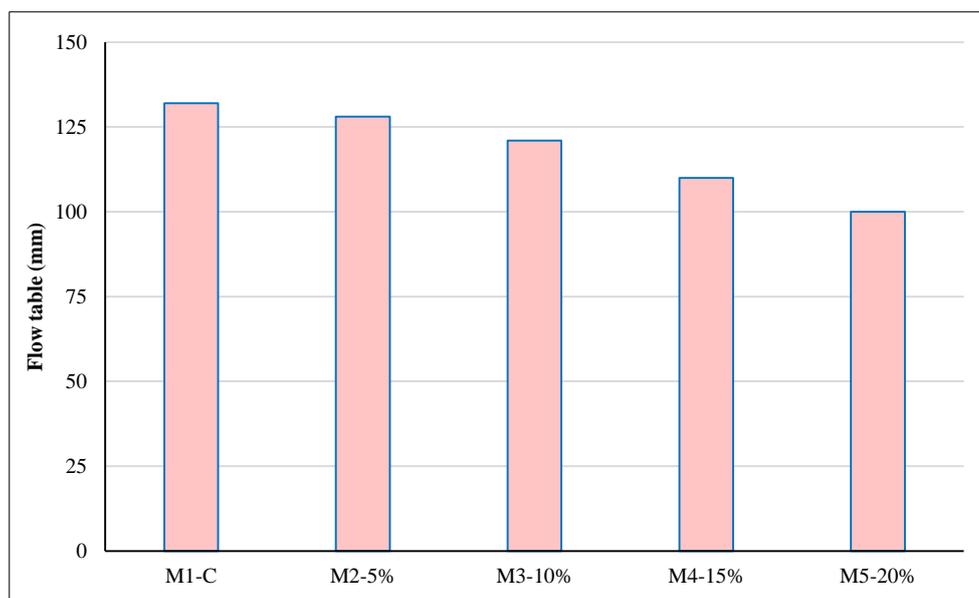


Figure 7. The results of the flow table test for mortar mixes

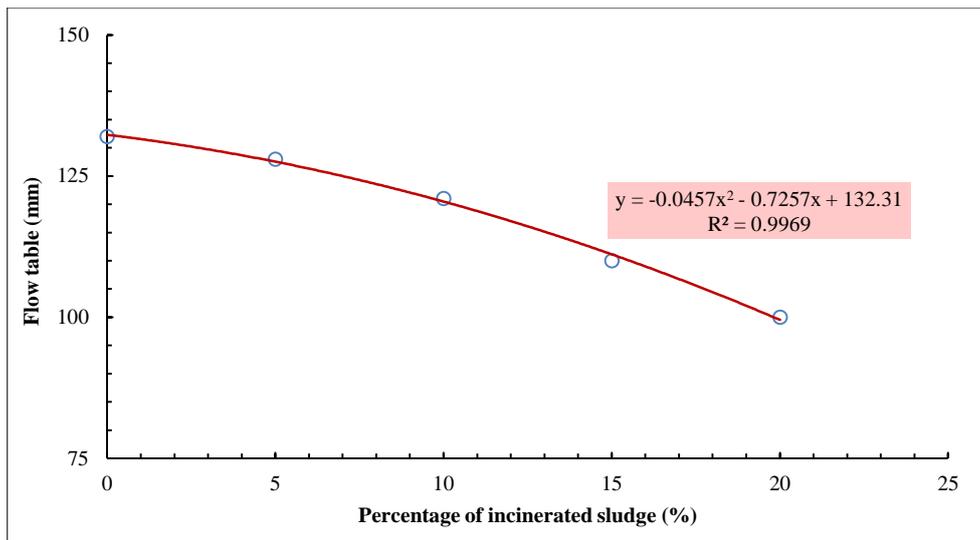


Figure 8. A regression model for simulating the flow table test for mortar mixes

The decrease in workability is due to the irregular morphology and high absorption of sludge particles. Also the high surface area (1100 m<sup>2</sup>/kg) compared to that of silica sand will result in less available water for lubrication and workability, and also due to the high porosity of sludge particles. The other possible explanation is that the change in aggregate gradation brought on by the addition of sludge may have an impact on the amount of water and cement needed to make the mix workable [21].

However, to maintain a certain level of consistency and workability, a higher water-to-cement ratio or high range water-reducer superplasticizer is necessary to increase the water content to give normal consistency of mortar [22], or by adding coal fly ash to mortars containing sludge, the reduction in workability may be partially eliminated [23]. This enables sludge to replace more cement and hydrate materials for a more extended period of time and enhances the end product's pozzolanic qualities.

### 3.2. Density

In order to determine the sample's density, the specimens were dried in an oven set to a temperature of 105°C until the constant mass is obtained. The specimen's dry mass in grams to the nearest 0.1% is then recorded, and the dry bulk density is calculated by dividing the dry mass in grams over the volume that it occupies in cubed centimeters. Figures 9 and 10 show the dry density results of different mortar batches. As the percentage of incinerated sludge increases, the dry density of mortar specimens decreases for all curing ages. This reduction in dry density is mainly due to the lower density (SG = 1.92) of sludge compared to that of silica sand (SG = 2.63), where the produced particles by the calcination process have more interior voids and, as a result, has lower specific gravity than silica sand. da Silva et al. [21] reported the same trend for specimen density and attributed that as a result to the lower specific mass of sludge, which in this case corresponds to the lower sample density.

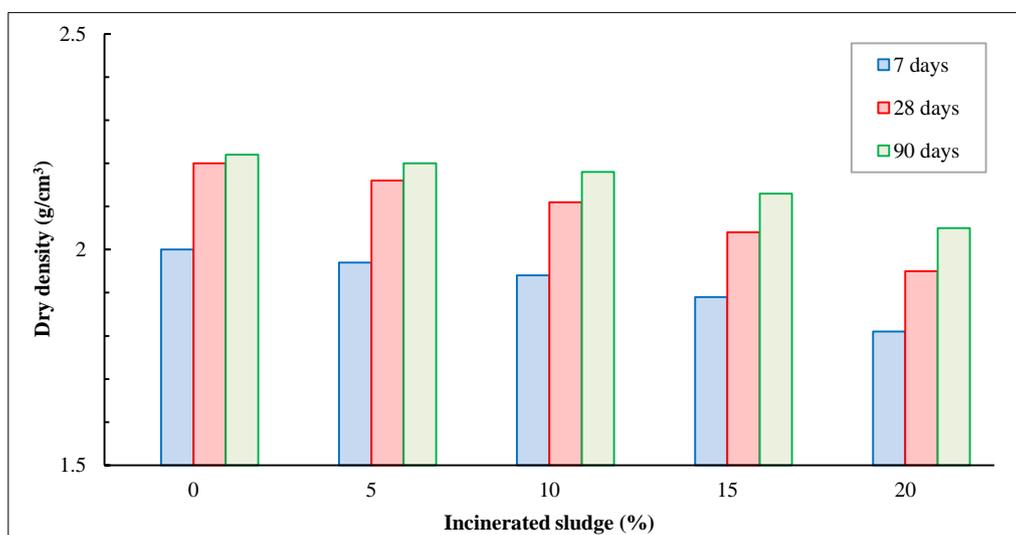


Figure 9. The dry density of mortar samples with different sludge replacement

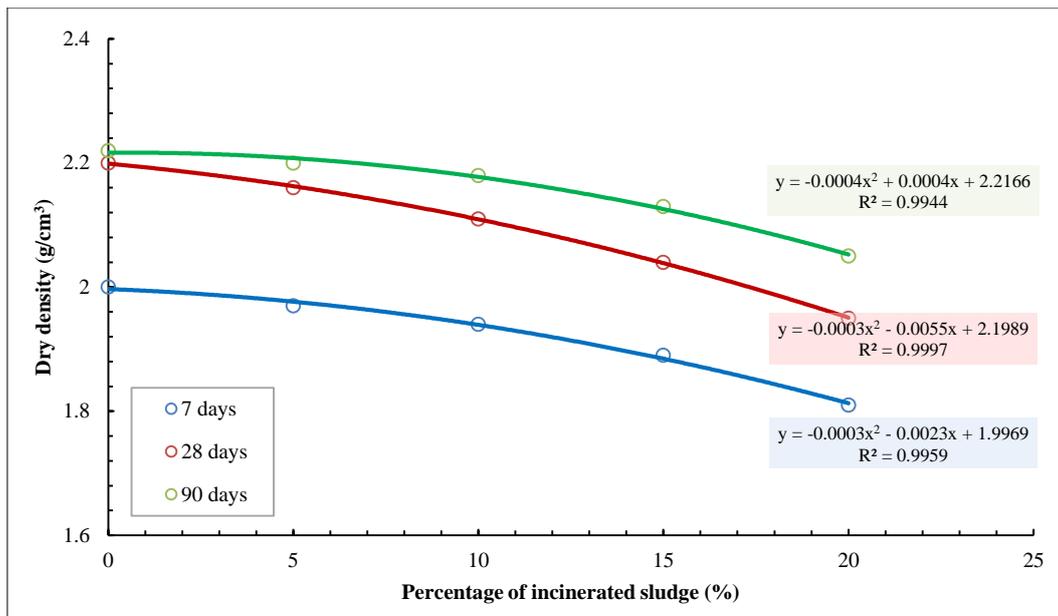


Figure 10. Regression models for the dry density of mortar samples with different sludge replacement

Although the density of sludge-containing samples was lower than the control samples, it can be observed that the increase in density for sludge-containing samples was higher than control samples after 90 days of curing age, which is attributed to the effect of the hydration process, which was insignificant during 7 and 28 days of curing.

### 3.3. Water Absorption of Mortar

The results of water absorption (Figures 11 and 12) showed an increase in water absorption capacity with the increased sludge content in comparison to control samples for all curing ages, especially for mortars with high sludge content (>10%), which may affect the mortar durability. The roughness and irregularity can explain this increase, low fineness of sludge particles, and high-water absorption capacity of sludge particles [20, 22], which contributes to the increase in the number of open pores of dried specimens, where water easily penetrates into mortar [15, 24]. Also, according to Andrade et al. [25] and Ramirez et al. [26], the increase in sludge particles porosity due to the calcination process leads to the increase in water absorption of sludge samples. However, water consumption can be reduced as a result of the usage of some mineral admixtures, such as fly ash, which are known to have the opposite effect [20]. Moreover, Samples with sludge content showed a higher increase in the rate of water absorption at 90 days of curing, mostly indicating a slow rate of hydration through the pozzolanic reaction [27].

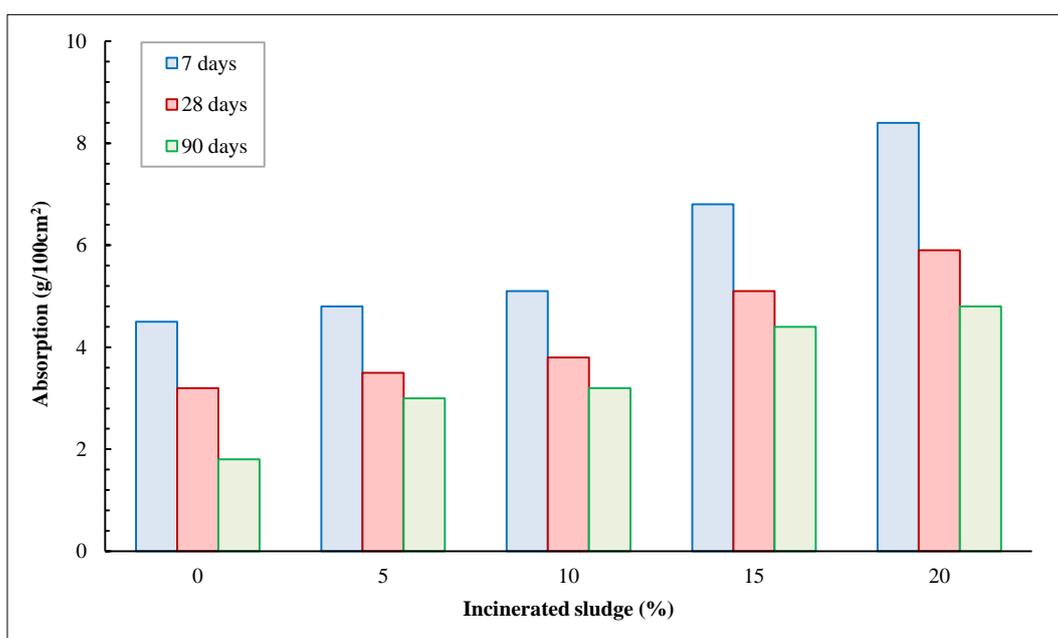


Figure 11. Water absorption of mortars with different percentages of sludge replacements

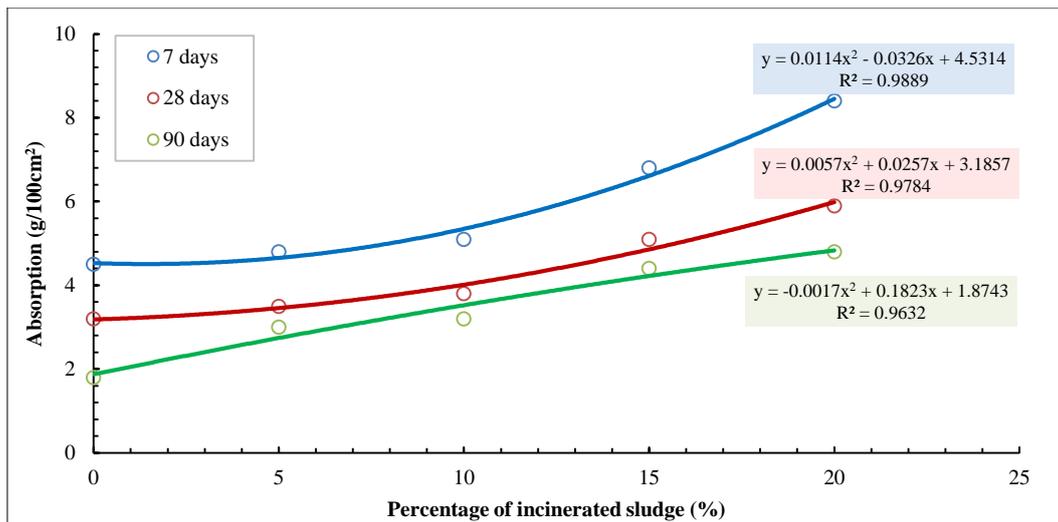


Figure 12. Regression models for water absorption of mortars with different percentages of sludge replacements

### 3.4. Compressive and Flexural Strengths

As mentioned previously, compressive and flexural strength tests will be conducted in this study, where the flexural strength adopted an indirect approach as explained by Al-hourri [28]. The results of compressive and flexural strength of mortar samples are represented in Figures 13 to 16.

The results show higher compressive and flexural strength for control samples compared to other mortar samples containing sludge for 7 and 28 days of curing. Also, the results showed a noticeable increase in compressive and flexural strength of samples containing 5% and 10% of sludge at 90 days compared to the curing age of 28 days. This increase improved the compressive and flexural strengths for 5% and 10% of sludge samples to be even higher than control samples. The increase was 1.5% and 3% for compressive strengths, 2% and 5% for flexural strength in 90 days of curing for 5% and 10% of sludge replacement, respectively. This improvement in compressive and flexural strengths at 90 days of curing age is due to the matrix of the high porosity of the sludge, resulting in more water to be absorbed, which affects the hydration process during the time, the relatively high reactivity of sludge caused by the high content of CaO and amorphous silica, and also the late development rate of pozzolanic reactivity in the incinerated sludge composition [21, 29], which takes more time for hydration process to be completed to form compounds possessing binding properties [18, 27]. These findings confirmed the results of Li et al. [19], in which mortars of 5% sand replacement with 900°C heat-treated sludge showed higher compressive strengths for all curing ages as reference mortars. This increase was attributed to the pozzolanic characteristics that sludge possessed during the heating process. In addition, according to Liang et al. [30] the rise in temperature increases the amount of amorphous SiO<sub>2</sub> in sludge, encouraging the formation of C-S-H gel in a mortar and improving mortar performance. Furthermore, according to the research conducted by Donatello et al. [31] compressive strength of mortar increases as the particle size of the added sludge decreases. Also, the chemical reaction between cement and silica sand could be improved due to the high fineness of sludge particles, thus resulting in a noticeable improvement in strength [32, 33]. This explanation agrees with Pan et al. [34], who concluded that the compressive strength of mortar made with fine sludge particles is greater than that of mortar made with coarse particles, where the fine particles provide sites for cement hydration reaction and the grinding process can enhance the pozzolanic activity of sludge.

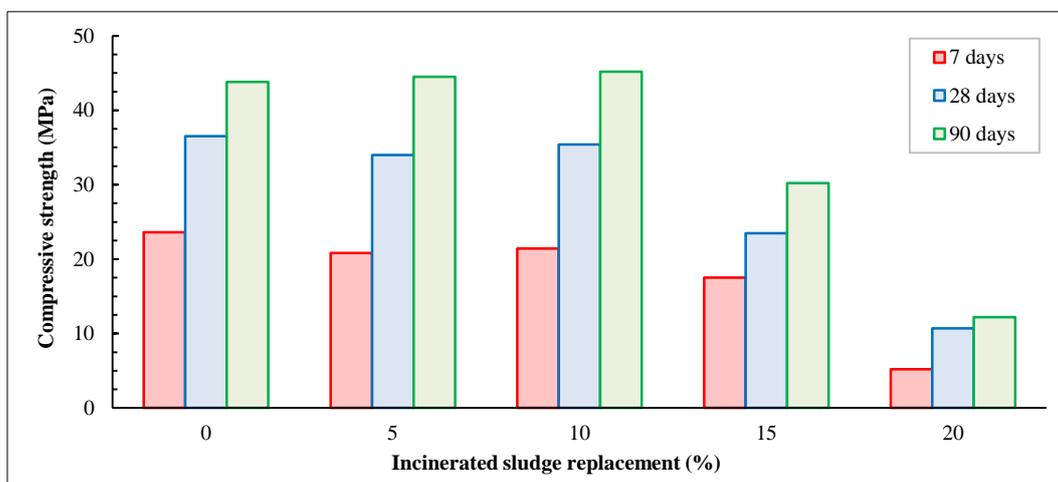


Figure 13. The results of compressive strength of mortar mixes

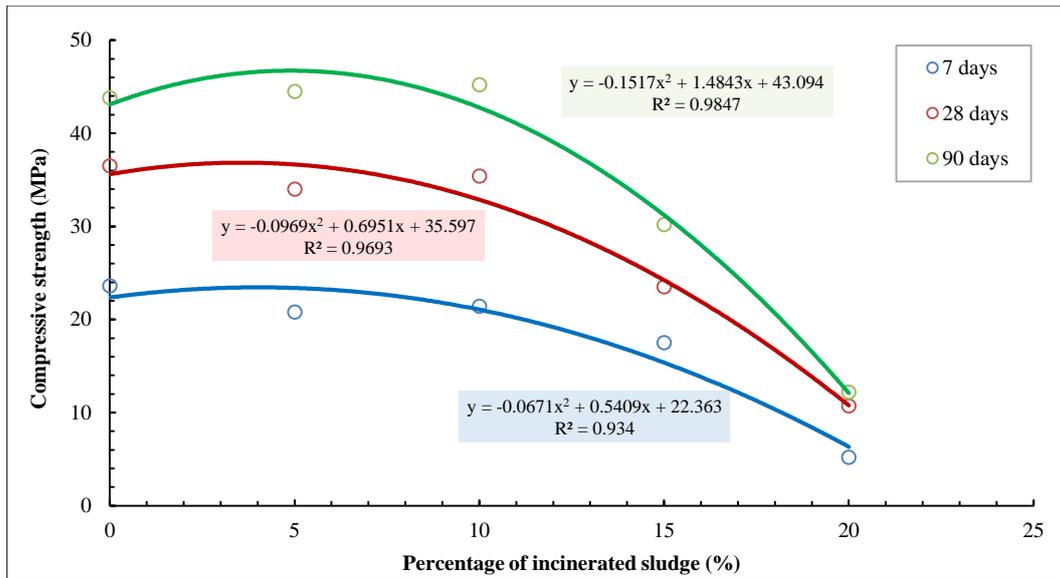


Figure 14. Regression models for the compressive strength of mortar mixes

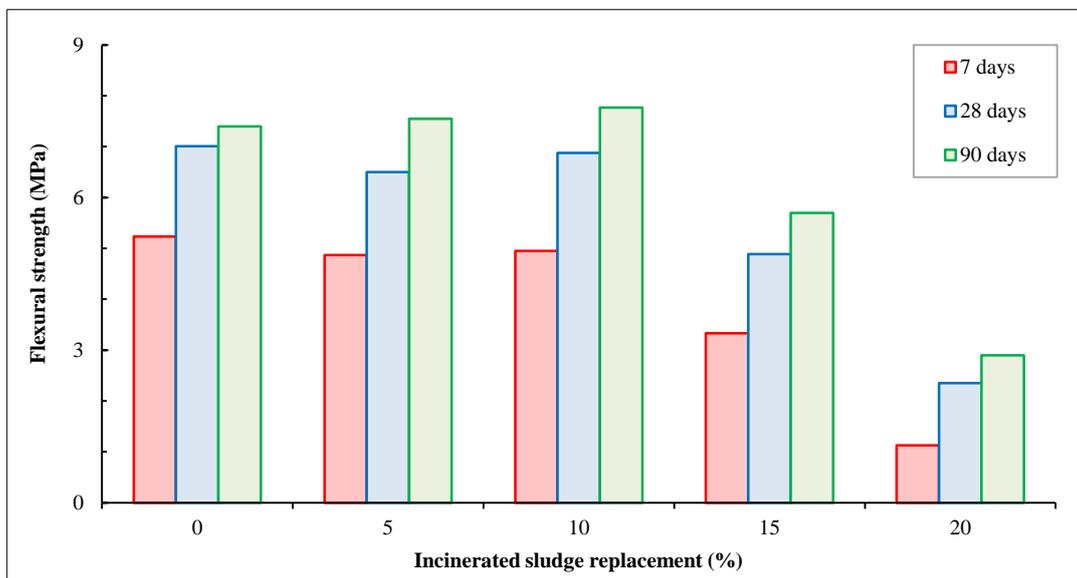


Figure 15. Regression models for the flexural strength of mortar mixes

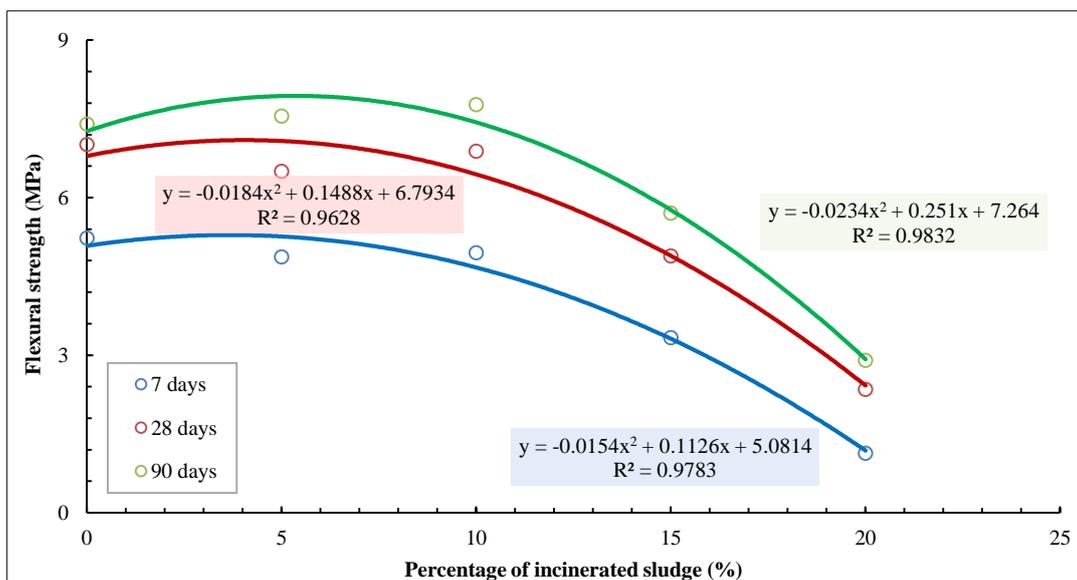


Figure 16. The results of compressive strength of mortar mixes

Another research conducted by Chen & Chi Sun [35] concluded that the improvement of long-term compressive strength for mortar incorporated with sludge is due to the internal curing of porous structure caused by the high-water absorption and porous structure of sludge, demonstrating long-term pozzolanic action.

Despite this, the replacement of sand with incinerated sludge (>10%) led to a significant reduction in compressive and flexural strength in all curing ages compared to that for control samples. Generally, low strength is attributed to the porous structure of the sludge particles resulting in high pore volume [26, 36], where fewer available spaces for the hydration process result in poor bonding between cement and fine aggregates [25, 37]. Furthermore, water demand is due to the high absorptivity of sludge particles compared to silica sand reaction [38]. Wang et al. [39] also confirmed the influence of high porosity and irregular shape on compressive strength. However, the effect of pozzolanic reaction was not enough to compensate for the high pore volume of 15% and 20% of sludge samples, where the results show a great reduction in compressive strength by 35.6% and 31% for 15% sludge replacement, 70% and 60.7% for 20% sludge replacement at 28 and 90 days of curing age, respectively.

### 3.5. Ultrasonic Pulse Velocity (UPV)

Figures 17 and 18 show the results of UPV on mortar samples for 7, 28, and 90 days of curing. The results of 7 and 28 days of curing show relatively higher UPVs values for control samples than other samples, where specimens with 5% and 10% show a somewhat higher rate of increase in UPVs at 90 days of curing, with values of 4.55 km/s and 4.58 km/s, respectively. However, this behavior could be attributed to the low rate of hydration and low rate of pozzolanic reaction for samples containing 5% and 10% of sludge. In contrast, the control samples show a higher rate of hydration, resulting in higher velocity values at 28 days of curing, which also explains the higher values of compressive and flexural strengths for the same curing age, where the quality of mortars was superior to other samples. However, samples with 15% and 20% of sludge content show low values of velocity with 3.1 km/s and 1.42 km/s for 28 days of curing and 3.15 km/s and 1.44 km/s for 90 days of curing, respectively, which might be explained due to the high void volume of sludge particles [40]. Also, all samples show an increase in UPVs values with the increase in curing age, indicating a direct relationship between UPVs and compressive strength values, where higher compressive strength shows a higher velocity value.

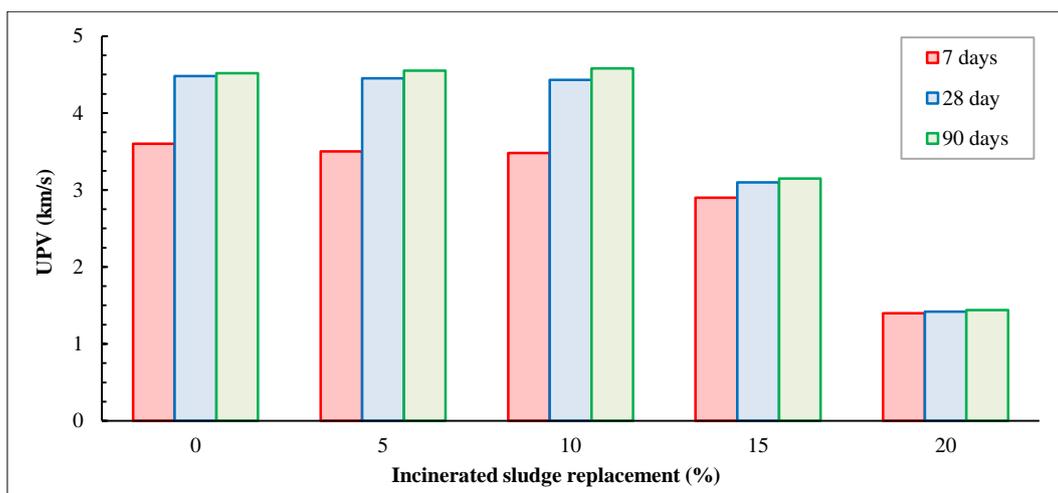


Figure 17. The results of the UPV test of mortar mixes

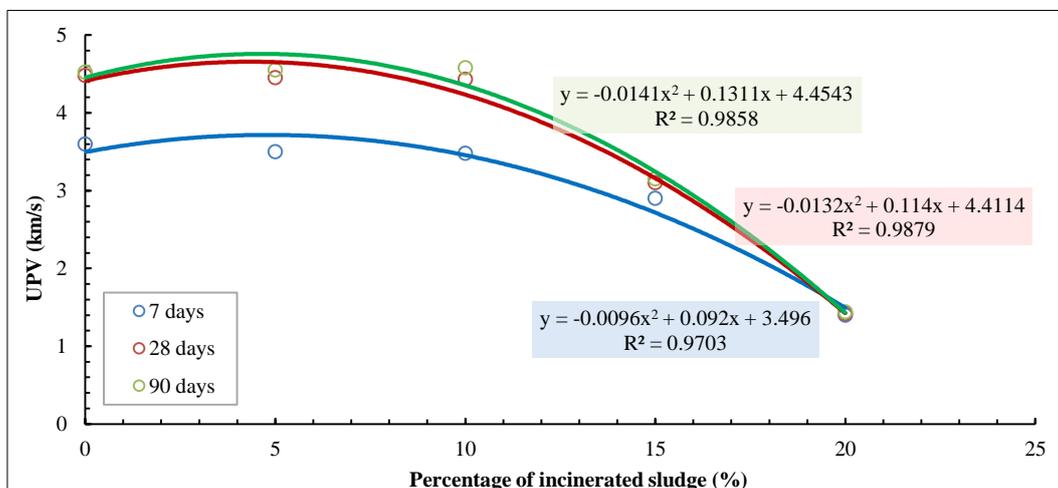


Figure 18. Regression models for the UPV test of mortar mixes

## 4. Conclusions

The present research aimed to assess the possibility of using water purification wastes from water treatment plants that are subjected to thermal treatment in the production of mortars. Based on the findings presented in this work, the following can be concluded:

- A slight decrease in workability and density for mortars with silica sand replaced up to 10% by the incinerated sludge was observed. In addition, higher levels (>10%) of sludge content can significantly reduce mortars' workability, density, and other mechanical properties;
- The absorption of mortar increased in parallel with the increase of sludge replacement due to the porous texture of sludge, but this increase is inconsiderable for mortars with low sludge substitutions (5% and 10%) compared to the control sample;
- Mortar samples with 5% and 10% content of sludge showed the best behavior regarding workability, density, absorption, and mechanical properties;
- Due to the high absorptivity of sludge, adding a water reducer superplasticizer is considered necessary to avoid a reduction in mechanical strength and workability;
- Mortars with 5% and 10% of sludge show UPVs values higher than the control samples at 90 days of curing, indicating the high quality of mortars due to the pozzolanic reaction of the sludge occurring slowly. Furthermore, UPVs values show a direct relationship with compressive and flexural strengths, where a higher velocity value gives higher compressive and flexural strength, indicating the high quality of mortars;
- Due to its pozzolanic reactivity, water purification sludge could be a great asset to meet construction needs;
- The use of water purification sludge in mortar mixes as a partial replacement for up to 10% of sand could be one of the sustainable management options in the process of sludge disposal. At the same time, it can contribute to the reduction in natural sand consumption.

Further works are still needed in this field to understand the impact of incinerated sludge on the performance of other types of concrete, including those with recycled aggregates such as rubberized concrete or plastic incorporated concrete. Moreover, the behavior of this mixture with other cementitious materials is still a gap in the literature that needs to be addressed.

## 5. Declarations

### 5.1. Author Contributions

Conceptualization, M.R., A.A., and S.H.; methodology, S.H., I.Y., and M.N.; formal analysis, M.R. and I.Y.; investigation, I.Y., A.A., and M.N.; writing—original draft preparation, M.R. and A.A.; writing—review and editing, S.H., I.Y. and M.N.; visualization, M.R. All authors have read and agreed to the published version of the manuscript.

### 5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

### 5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 5.4. Conflicts of Interest

The authors declare no conflict of interest.

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